A STUDY OF ELECTRONIC METHODS FOR THE MEASUREMENT OF SMALL DIRECT CURRENTS

Technical Report to
The Office of Naval Research
under Contract No. Nonr 580(00)580(01)

ENGINEERING AND INDUSTRIAL EXPERIMENT STATION

College of Engineering

University of Florida

Gainesville

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by

John H. Searcy

This report describes the information obtained in a preliminary phase of the research in progress on "A Study of Negative Gaseous Ions". It consists of a thesis presented to the Graduate Council of the University of Florida in partial fulfillment of the requirements for the degree of Master of Science in Engineering.

Department of Electrical Engineering

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1 June, 1953

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ABSTRACT

A survey of methods employed for the measurement of small currents in the range from 10^{-11} to about 10^{-15} amp. is presented with particular attention given to various methods of reducing drift in d-c amplifiers used for the measurement of such currents. The problems involved in designing a stable power supply are also considered. Experimental results obtained from three types of a-c ope electrometer amplifiers are presented. These are: (1) a unity feedback electrometer employing a Victoreen VX-41A tube, (2) a batteryless electrometer circuit employing a General Electric FP-54 tube, and (3) a new type of electrometer circuit utilizing nonlinear capacitors.

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INTRODUCTION

Certain scientific investigations require the measurement of currents of very small magnitude that are beyond the capabilities of even the most sensitive galvanometers. Most noteworthy are the ion currents in mass spectrometer and ionization chamber work and also the small electron currents from high vacuum photoelectric cells used to measure very weak light flux. Such currents may range from 10^{-11} to 10^{-16} amperes or lower.

Much of the experimental work reported in this paper concerns methods used to measure ion currents in a mass spectrometer designed for the study of negative gaseous ions. This work is being conducted by the Department of Electrical Engineering and the Engineering and Industrial Experiment Station at the University of Florida by contract with the Office of Naval Research under Contract Number Nonr 580(00)580(01).

For determining the value of very small currents, instruments have been evolved which either measure the potential developed across a high resistance, of the order of 10^{11} ohms, through which this current is flowing, or else measure the rate of change of potential of a charged

conductor due to these currents. The electroscope was the first instrument employing the latter method. It was used in early work on the measurement of radioactivity in conjunction with an ionization chamber.

The apparatus was arranged as shown in Fig. 1.1. A charge was placed on the collector and leaves of the electroscope. The intensity of ionization, and hence radioactivity, then being indicated by the rate of decline of the deflection of the electroscope leaves. Refinements consisted of an automatic recharging device which worked

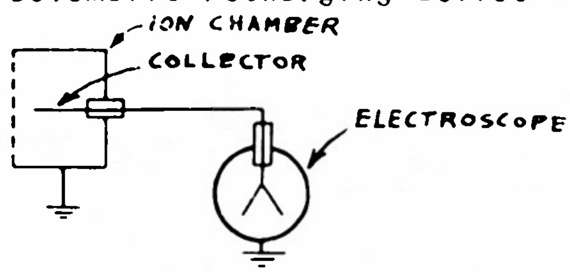

Figure 1.1 - Ion Chamber and Electroscope

on the principle that as the leaves of the electroscope collapsed they contacted a charged conductor and were recharged. An alternate scheme consisted of applying a constant potential to the ion chamber in series with a high resistance, and as mentioned previously, measuring the potential drop across the resistor due to the ion current with a quadrant electrometer. The latter form of operation, with the quadrant electrometer replaced by a electrometer tube and D.C. amplifier, is used in some modern types of radioactivity meters.

An electrometer is a device for measuring electric potential. In its most simple form it consists of a calibrated electroscope. Electrometers have taken many forms such as the string, quartz thread, capillary, gold leaf, and quadrant electrometers, but all these early forms worked on the same principle, namely electrostatic attraction of oppositely charged conductors. The quadrant electrometer received much attention from the early workers and reached a high state of development. A rather remarkable sensitivity was obtained from special forms of the quadrant electrometer, an example is the Compton quadrant electrometer which, by careful adjustment, can be made to read 10,000 scale divisions per volt with a scale distance of one meter.

The principle drawback to the use of the quadrant electrometer is that high sensitivity demands extraordinarily delicate construction and adjustment. Many of the disadvantages of the quadrant electrometer can be avoided if a vacuum tube electrometer is used. Ideally, a control grid maintained negative with respect to the cathode, would control the plate current with no loss of charge. Unfortunately, this ideal condition is never realized. In fact, most tubes designed for radio receiver use have grid currents so large that it is not advisable to use grid resistors larger than several megohms. Metcalf and Thompson (1)* undertook a study of

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*Numbers in parentheses indicate reference listed in the bibliography at the end of this paper.

grid currents which resulted in the now well known General Electric FP-54 electrometer tube. By means of special construction and operation it is possible to reduce grid currents to 10^{-16} amp., which permits currents of the order of 10^{-16} amp. to be detected. Nelson (2) describes a method for reducing grid current of a triode by operating the tube backwards, that is, by making the plate serve the function of the control electrode while the grid serves as the plate. The grid is operated at approximately four volts positive with respect to the cathode, and serves as the indicating electrode as well as to repell positive ions emitted from the cathode, that would normally be attracted to the negative control electrode. A tube operated in this manner is called an inverted triode and the result is a considerable reduction in grid current at the expense of sensitivity. Several tubes of this type were manufactured by Westinghouse. Generally a tetrode electrometer tube such as the FP-54 is preferable because of higher sensitivity and lower grid current.

High sensitivity from electrometer tubes demands that some means be used to reduce the effects of power supply voltage fluctuations and effects due to ageing of the tube, etc. These effects produce a shift in the zero point of the galvanometer or other indicating device. In the past, the problem of a stable source of power has been solved by the use of large storage batteries with operation restricted to from about 90 to 50 per cent of full charge. Various forms of balanced one and two tube circuits (3, 4, 6) where developed

to render the electrometer circuit insensitive to battery voltage variations of small magnitude. The most successful of these are the DuBridge and Brown circuit (6) and the split electrometer tube (9, 10). Storage batteries, to say the least, are undesirable for several reasons and have resulted in a recent trend to a-c power line operation using electronically stabilized power supplies (11, 12, 13). The degree to which various forms of drift and general instability have been reduced is shown by the fact that special circuits using power line operation often have drifts of only a millivolt or so over a 24 hour period (12).

A recent development is the vibrating-reed electrometer (14, 15). A continuously vibrating reed which, through its oscillating capacitance to a fixed electrode, converts the voltage drop in the high value input resistor to an approximately sinusoidal alternating potential. The a-c signal is then amplified by a stable audio frequency amplifier. This instrument has a sensitivity comparable to the FP-54 tube and can be made unusually free from troublesome zero drift. Drifts are usually about one third (or less) of a mv. per day and are due mainly to variations of contact potential on the vibrating reed.

This thesis is concerned with electronic methods, that is, methods employing vacuum tubes, for the measurement of small currents. In particular, it will present the following items:

1. A study of the electrometer tube with attention given to methods of reducing grid current, and means for improving circuit stability.

2. A study of the causes of drift in d-c amplifiers and a survey of special circuits developed for minimizing drift.

3. A consideration of the problems encountered in the design of stable a-c line operation of power supplies for use with electrometer tube circuits.

4. Data obtained from three experimental electrometer circuits.

SECTION 2

THE ELECTROMETER TUBE

2.1 Grid current.-- If a vacuum tube is to be used to amplify small currents, steps must be taken to reduce grid currents. Commercial radio tubes, operated under normally specified conditions, have a grid current of approximately 10^{-9} amp. and are usually unsuitable for small current work, but exceptions in the case of certain tubes, when operated at low voltage, should be mentioned (11, 12, 13). Vacuum tubes have been especially constructed for such use. Such tubes are called electrometer tubes.

Metcalf and Thompson (1) list six sources of grid current:

1. Leakage over insulation.
2. Ions formed by gas present in the tube.
3. Thermionic grid emission due to indirect heating by the cathode.
4. Ions emitted by the cathode.
5. Photoelectrons emitted by the control grid under action of light from the cathode.
6. Photoelectrons emitted from the control grid by soft X-rays produced by the normal anode current.

Steps taken by Metcalf and Thompson to reduce grid current were:

1. Leakage minimized by bringing the grid lead out at the top of the tube.

2. The use of a low anode voltage to reduce ionization of gas in tube and to reduce effects of soft X-rays.

3. Effects of grid heating and photo emission reduced by using a thoriated filament operated at low temperature and the use of large open structures.

4. Positive ions emitted by the filament are repelled by a positive space-charge grid placed between filament and control grid. This grid also increases transconductance.

Such principles of construction and operation are incorporated in the FP-54 electrometer tube manufactured by the General Electric Company. Typical operating conditions are specified as:

Filament voltage	2.5 volts
Plate voltage	6.0 volts
Control grid bias	-4.0 volts
Space-charge grid voltage	4.0 volts
Filament current	90.0 ma.
Plate current	40.0 μa.
Transconductance	20 μmhos
Amplification factor	0.9
Plate resistance	45,000 ohms

Tubes with simiiar characteristics by other manufacturers include, among others,

Western Electric Co.	Type D-96475	grid current $\sim 10^{-15}$ amp.
Victoreen Inst. Co.	Type VX-41A	grid current $\sim 10^{-15}$ amp.
Raytheon Mfg. Co.	Type CX-570A	grid current $\sim 10^{-14}$ amp.

For the measurement of currents greater than 10^{-13} amp., grid current may be neglected, but for smaller currents grid current should be subtracted from the indicated value. Typical grid current characteristics for the FP-54 are shown in Fig. 2.1.

For very small currents, and also for the measurement of grid current, a method based on the rate of change of grid

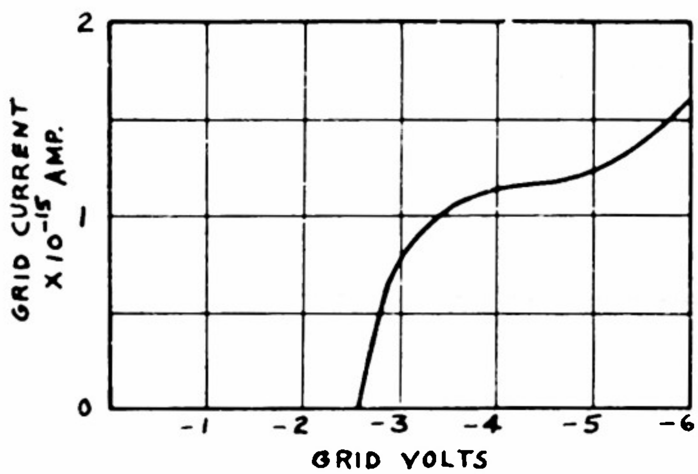


Figure 2.1 - Grid Current Characteristics of FP-54 Electrometer Tube

potential is used. In order to use this method the plate current vs. grid voltage characteristics must be determined by applying an accurately known voltage to the grid, by means of a potentiometer, and measuring plate current. The grid capacitance must also be known but can be determined easily and accurately by standard techniques. The grid is biased to some known voltage and then disconnected, i.e., allowed to "float". Plate current now serves to indicate grid potential, e_g. Grid current is given by,

$$i_g = C \frac{de_g}{dt} \quad . \tag{1}$$

Where C is the total capacitance of the grid circuit. After the relationship between grid current and grid voltage is determined, it may be plotted and used for correction. This is the method used by the manufacturer to check grid current.

2.2 Sensitivity attainable.--The electrometer tube owes its usefulness to the low magnitude of grid current. Even though transconductance is only 20 μmhos, considerable amplification is possible because large grid resistors may be used. This can be shown as follows,

$$\Delta e_g = \Delta i_a R \tag{2}$$

where, Δe_g = a small change in grid voltage,

Δi_a = a small change in the current to be measured which is flowing in R,

R = grid resistor

also,

$$\Delta i_p = \Delta e_g g_m \tag{3}$$

where, i_p = plate current,

g_m = transconductance.

Simultaneous solution of equations 1 and 2 for i_p gives,

$$\Delta i_p = \Delta i_a R g_m \, .$$

From which,

$$\text{current amplification} = \frac{\Delta i_p}{\Delta i_a} = g_m R \quad . \tag{4}$$

An FP-54 used in conjunction with a grid resistor of 10^{11} ohms allows a current amplification of,

$$\frac{\Delta i_p}{\Delta i_g} = (2.0 \times 10^{-5})(10^{11}) = 2.0 \times 10^{6}$$

If a galvanometer with a sensitivity of 4×10^{-10} amp./mm. is connected in the plate circuit, a current sensitivity of 2×10^{-16} amp./mm. is obtained.

2.3 Installation precautions.--A number of precautions must be observed if full advantages of the low grid current properties of an electrometer tube are to be realized. The surface of the tube, especially around the grid lead, must be kept free from all sources of leakage. The tube envelope should be washed with alcohol before use. Ideally, the tube should be kept in a vacuum, but if this is not practical the air in contact with the tube should be kept dry with a drying agent such as phosphorous pentoxide placed in a shielded box with the tube.

2.4 Circuits used to reduce drift.--When an electrometer tube is used to measure extremely small currents, special circuits to neutralize the effects of battery drift and variations in the thermionic emission of the filament are required. Generally speaking, all neutralizing schemes developed use a balanced bridge arrangement. The most successful of such circuits are balanced both for power supply and filament emission fluctuations.

<u>2.41 Two tube bridge circuit.</u>--A two tube circuit recommended by DuBridge (3) is shown in Fig. 2.2. In this circuit R_{L_1}' is varied until small changes in plate voltage, brought about by changing R_3, do not affect the galvanometer deflection. Furthermore the contact on R_1 is adjusted until small changes in R_2, controlling the filament current, leave the deflection unchanged. The galvanometer zero is restored after every

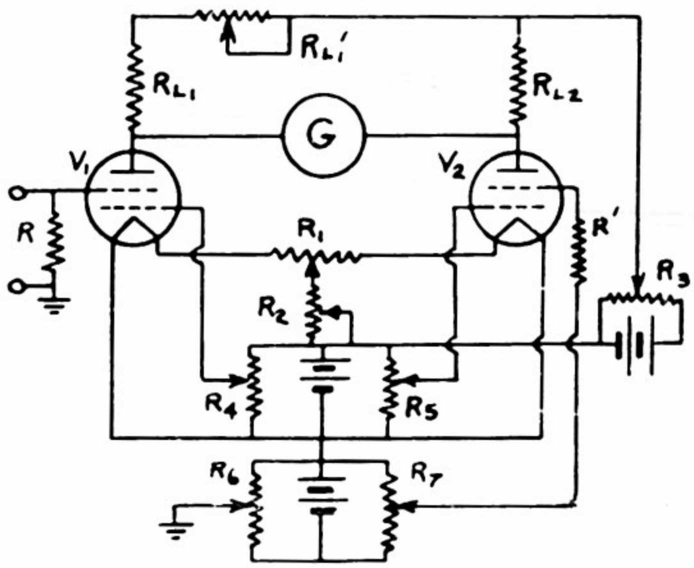


Figure 2.2 - Two Tube Electrometer Circuit

adjustment by readjusting grid potentials by means of R_7 and R_6.

Best results are obtained with matched tubes. A matched pair must be selected, since there are large variations between individual tubes. This is a rather serious disadvantage since the FP-54 is rather expensive. This coupled with the fact that the circuit is not balanced

for random filament emission fluctuation between the individual tubes has resulted in the development of one-tube balanced circuits.

2.42 Soller circuit.--One of the first balanced one-tube circuits was devised by Soller (4). The circuit is shown in Fig. 2.3 together with a simplified equivalent circuit in which r_p is the plate resistance of the electrometer. The tube forms one arm of a Wheatstone bridge. The plate current (I_p) characteristics as a function of supply voltage (E_b) is shown in Fig. 2.3(c). This curve is the result of the simultaneous variation of plate voltage, grid bias, and filament current, since they all originate from the same source. At the operating point, o, the tube can be assumed to be replaced by a resistance determined by the negative slope of the tangent line to the curve at o in series with a source of voltage E_p, which is determined by the intercept of the tangent line and the E_b axis.

Balanced conditions against variations in the supply current, I_b, require that

$$\frac{r_p}{R'} = \frac{R_L}{R_4} \tag{5}$$

Where, $R' = R_1+R_2+R_3+$ filament resistance.

A bridge with a scurce of voltage in one arm such as E_p, will have an unbalanced output, E, which is given by

$$E = E_p \frac{R_L}{r_p+R_L} \quad . \tag{6}$$

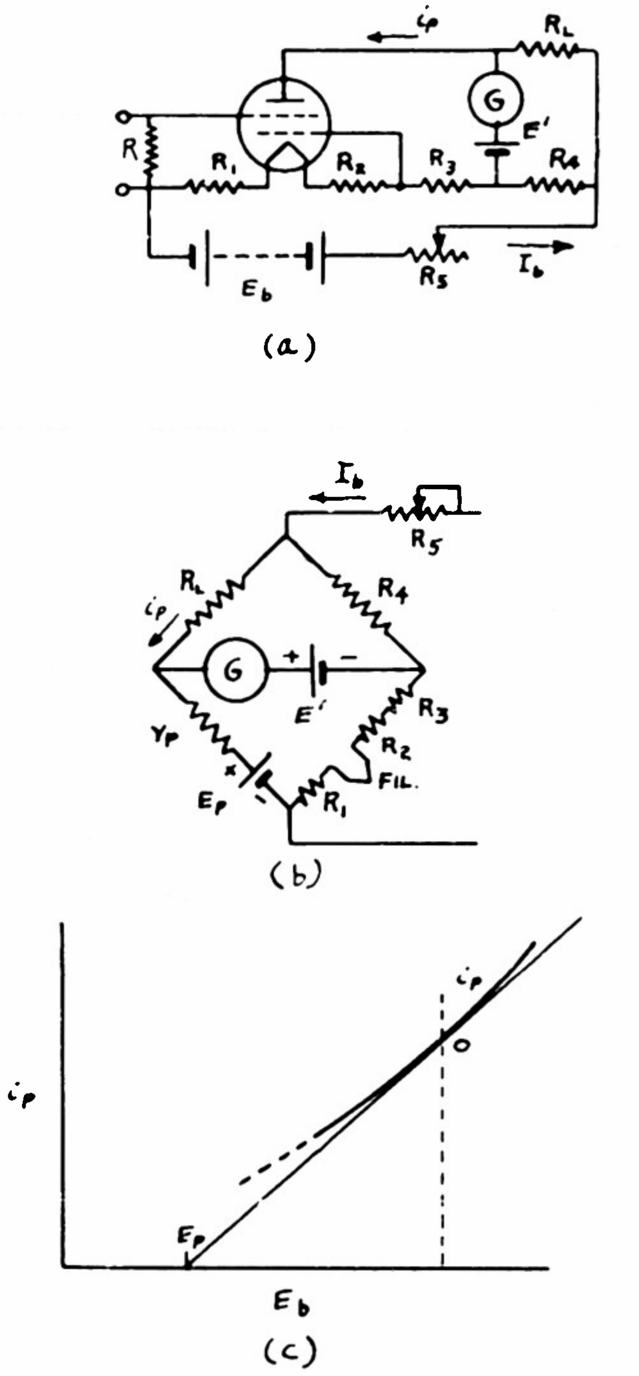
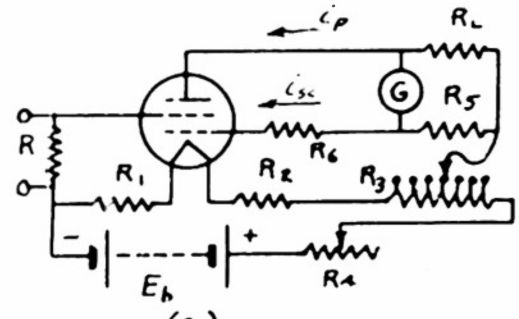


Figure 2.3 - Soller One Tube Circuit

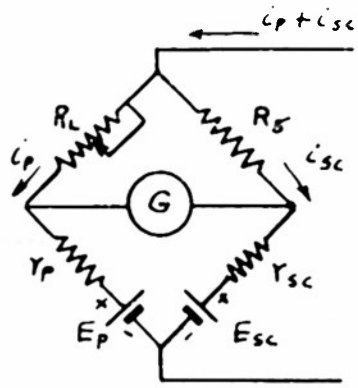
The purpose of the battery in the galvanometer circuit is to cancel out this voltage. Range of balance is limited by the curvature of the tube characteristics. This curvature causes r_p and E_p to change with changes of battery voltage, E_b. Turner and Stiegelin (5) point out that the battery E' should have a voltage near E, since R_L must be determined from equation 6 once E' is selected. If E' is too small, R_L must be correspondingly low, which results in a loss of sensitivity because R_L is essentially in shunt with the galvanometer. Since R_4 is determined by the filament current requirements, it is of relatively low resistance compared with R_L. The most serious objection to the Soller circuit is the necessity for battery E'. Variations in the potential of battery E' due to temperature and ageing effects appear directly in the galvanometer circuit. Also, the circuit is not balanced for random variations of filament emission.

<u>2.43 DuBridge and Brown circuit.</u>--A one tube circuit by DuBridge and Brown (6), which eliminates the battery in the galvanometer circuit and also offers a means for reducing the effects of filament emission variations, is shown in Fig. 2.4. Since space-charge grid current and plate current come from the same source, it may be assumed they will vary in the same ratio with variations of filament emission. For zero galvanometer deflection,

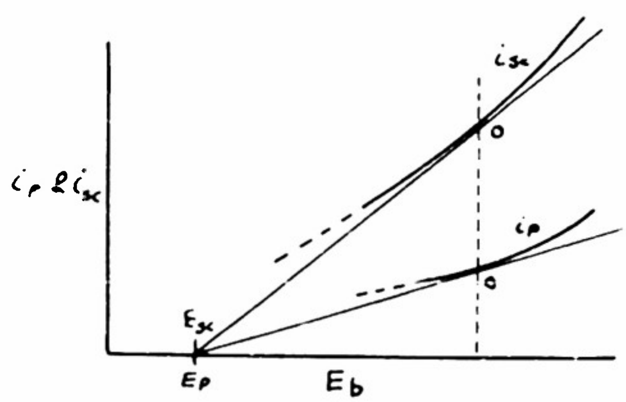
$$\frac{i_p}{i_{sc}} = \frac{R_L}{R_5} \quad . \tag{7}$$



(a)



(b)



(C)

Figure 2.4 - DuBridge and Brown One Tube Circuit

The voltage across the galvanometer is given by,

$$e = i_{sc} R_S - i_p R_L \quad , \tag{8}$$

which assumes that the galvanometer current is small compared to I_p or I_{sc}. For the galvanometer deflection to be independent of E_b (and hence I_b), $\frac{\partial e}{\partial I_b}$ must equal zero. That is,

$$\frac{\partial i_{sc}}{\partial I_b} R_S - \frac{\partial i_p}{\partial I_b} R_L = 0 \quad ,$$

or

$$\frac{\partial i_p}{\partial I_b} = \frac{R_S}{R_L} \frac{\partial i_{sc}}{\partial I_b} \tag{9}$$

For equations 7 and 9 to hold, it is necessary that the tangent lines to the I_p vs. E_b and I_{sc} vs. E_b characteristics curves intersect at the same point on the E_b axis as shown in Fig. 2.4(c). This is in general not true but is approximately true over a small range of E_b so that satisfactory balance can be obtained.

The circuit is first balanced for the condition expressed in equation 7 by varying R_L until the galvanometer deflection is zero. Rheostat R_4 is first adjusted for correct filament current. It is then slowly varied until a minimum in galvanometer deflection is reached, the galvanometer being kept on scale by adjustment of R_L. If at the minimum, the filament current is not within a few percent from the correct value, the tap on R_3 should be changed and the above adjustment repeated. It will usually be found that at correct balance the voltages on the plate, space-charge grid, and control grid are within about one-half volt of the recommended values.

The purpose of resistor R_6 is to provide a voltage drop so that the space-charge grid will be operated at the correct voltage.

2.44 Barth and Penick circuit.--Barth (7) and Penick (8) have shown that an extra degree of freedom for balancing the DuBridge and Brown circuit may be obtained by bringing the plate and space-charge grid connections to separate taps on R_3.

2.45 Split electrometer tube.--In work done to improve the stability of the FP-54, Fafferty and Kingdon (9) found that the DuBridge and Brown circuit cannot entirely eliminate fluctuations and drift due to filament emission because of the asymmetry of the space-charge grid and plate. The space-charge grid draws about four or five times as much current as the plate. Under these conditions it was found that the space-charge grid current and plate current do not change in the same ratio for changes in filament emission. Short-time fluctuations were found to be due to temperature limited conditions at the ends of the filament because of cooling by the lead wires. Long-time drift was found to be caused by a slow activation or deactivation of the filament. By operating the filament at a temperature at which activation or deactivation does not take place and placing shields over the ends of the filament, short-time fluctuations and long-time drift could be reduced.

Lafferty and Kingdon (op. cit.) (9) used a split electrometer tube in efforts to obtain better symmetry. The split electrometer tube consists of a common space-charge grid and filament, but separate control grids and plates which are geometrically similar and are symmetrically situated on each side of the filament plane as shown in Fig. 2.5(c). Insulation precautions are taken on only one grid since the other is not used for current measurement. A circuit used with the split electrometer tube is shown in Fig. 2.5(a).

In the bridge circuit using a split electrometer tube or a pair of matched tubes and a low resistance indicating device such as a galvanometer as shown in Fig. 2.5(b), maximum sensitivity is obtained when $R_{L_1} = r_{p_1}$ and $R_{L_2} = r_{p_2}$. Conditions for balance are:

1. $i_{p_1} = i_{p_2}$
2. $\frac{\partial i_{p_1}}{\partial E_b} = \frac{\partial i_{p_2}}{\partial E_b}$
3. $R_{L_1} = R_{L_2}$

The sensitivity is reduced by one-half due to the splitting operation and by one-half by the bridge circuit so that the overall sensitivity is one-fourth that of a single-tube circuit. Sensitivity can be increased by using a higher-efficiency, oxide-coated filament in place of the thoriated filament. The use of an oxide-coated filament also results in lower grid current because of the lower operating temperature which reduces currents due to photo-emission from the grid under action of light from the filament.

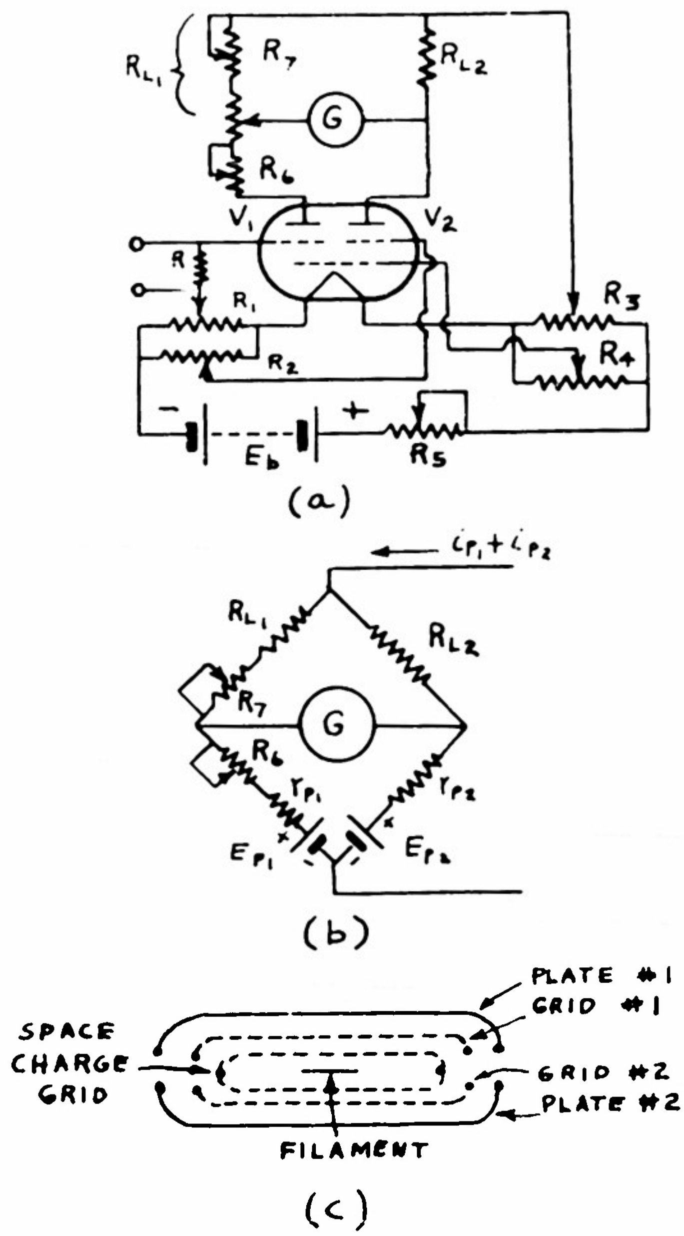


Figure 2.5 - Split Electrometer Tube and Circuit

The circuit is balanced as follows:

1. Set R_{L_1} to equal R_{L_2}.
2. Bias on V_2 is varied by means of R_2, to set I_2 equal to I_1.
3. R_5 is varied to cause changes in I which are then balanced out by fine adjustment of R_7 until no galvanometer deflections occur.
4. Slight adjustments may be necessary on R_6 to eliminate long-time drift.

Lafferty and Kingdon (op. cit.)(9) give performance data on a split electrometer tube, which in conjunction with a galvanometer with a sensitivity of 2×10^{-10} amp./mm., gave an overall sensitivity of 50,000 mm./volt and a long-time drift of less than two mv. per week. The short-time fluctuations were only three times as great as were computed due to the grid resistor and a bandwidth of one cycle per second. This tube was a modified FP-54 with a oxide-coated filament requiring 120 ma. at 1.5 volts.

Two commercially available split electrometer tubes are the Ferranti type DBM8A and the Compagnie des Lampes type 6196.

SECTION 3

METHODS FOR REDUCING DRIFT IN D-C AMPLIFIERS

This section will be devoted to a study of the most troublesome problem associated with d-c amplifiers, namely drift of the zero setting. D-c amplifiers following an electrometer tube are useful for increasing the current sensitivity to a degree so that less sensitive, more rugged, and usually more convenient indicating instruments than a string suspension galvanometer may be used. Even though the electrometer tube is a d-c amplifier, many of the circuits used are peculiar to it due to the special construction and operation. In particular, this section will be concerned with drift neutralizing methods as applied to amplifiers which follow the electrometer tube and use more conventional tubes and circuit components. Practically the same drift requirements as for an electrometer tube are placed on the first stage following an electrometer tube, because the electrometer tube provides no voltage amplification, but serves as an impedance matching device from the high value grid resistor to the input of the first stage. Since drift may be represented as a fictitious source of voltage in the cathode lead, large amplification in the initial stage is highly desirable in order to

override drift in the latter stages. For these reasons particular attention is directed toward neutralizing drift in the first stages of a d-c amplifier.

3.1 Causes of drift. --Drift in a d-c amplifier may be attributed to:

1. Variations in the value of circuit parameters, such as resistances.
2. Variations in plate voltage.
3. Variations in tube parameters.
4. Variations in filament emission.

The first of these can be eliminated by using stable circuit components, such as temperature-stable wire-wound resistors, good insulation, care in construction, etc. The second may be minimized by:

1. Use of stabilized power supplies and/or
2. Circuits which are balanced for variations in plate voltage.

The third cause of drift arises mainly from two sources, mechanical and electrical. Mechanical drift is caused by a shift in tube elements by thermal expansion or mechanical shock. These effects can be reduced by using low supply voltages and shock mounting of the tube. Drifts due to heating of the tube elements occurs largely during the initial warm up period after the amplifier is turned on. Electrical variation of tube parameters are largely due to conditions at the emitting surface of the cathode and so come under item four, variations in filament emission. These variations are

largely due to variations in filament supply voltage, ambient temperature changes, and to varying conditions at the emitting surface of the cathode. These effects may be termed the "effective contact difference of potential" between grid and cathode. A definite change in heater voltage is equivalent to a definite change in cathode-grid potential. For an oxide-coated cathode a ten per cent change in filament voltage is equivalent to approximately a 100 mv. change in cathode-grid voltage. As with plate voltage variations, the effects of cathode supply voltage variations can be reduced by using a lized power supply or cancelling circuits, or both.

After various schemes have been applied to a d-c amplifier to render it insensitive to power supply variations, it will be found that the remaining drift consists of a rather large short-time drift, lasting about an hour, as tubes come to a new temperature equilibrium and a long-time drift that decreases as the tubes age. In order to reduce the latter drift, new tubes are usually aged for about a week at normal filament voltage before being used in d-c amplifiers.

3.2 Circuits used to reduce drift.--Drift caused by variations in heater voltage may be cancelled by using the circuit shown in Fig. 3.1. A change in heater voltage causes a change in emission from both tubes, but if the diode plate current, I_d, is made much larger than the triode plate current, I_p, the increased current in R causes an increase in bias on the triode (or pentode), which if properly proportioned, will

reduce the plate current in the triode to the original value. This circuit is not compensated for variations of plate voltage or variations in random emission of the individual cathodes. A duodiode-triode tube, as used in radio receivers for second detector and first audio stage, might prove useful because of the common cathode.

Miller (17) has developed a cathode heater compensator circuit which employs a triode in place of the diode. Miller's circuit uses a double triode with a common cathode as shown in Fig. 3.2. Drift may be assumed to be caused by a fictitious source of voltage, Δe, in the cathode circuit. Miller's analysis shows for correct compensation that if

$$R_2 = \frac{1}{g_{m_2}} \qquad (1)$$

then

$$\Delta e = \Delta i_{p_1} R_1 - (g_{m_2} \Delta i_{p_1} R_1) R_2 = 0 \qquad (2)$$

Miller's analysis assumes that R_L is large so that I_{p1} is small compared to I_{p2}. Rittenhouse (18) has shown that no limitations need be placed on the value of R_L and that compensation will hold as long as equation 1 is true. Large heater voltage variations cause g_{m2} to change, thus compensation is tangential and is useful over a limited range, but still considerable improvement over an uncompensated circuit is obtained. This circuit is not compensated for plate voltage

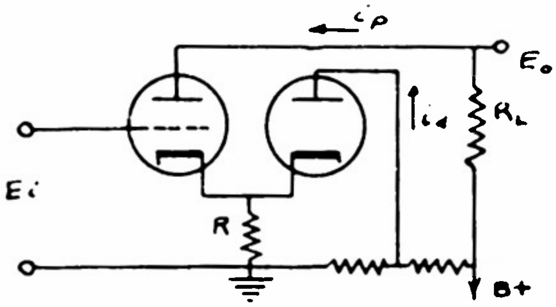


Figure 3.1 - Cathode Drift Cancellation with Auxiliary Diode

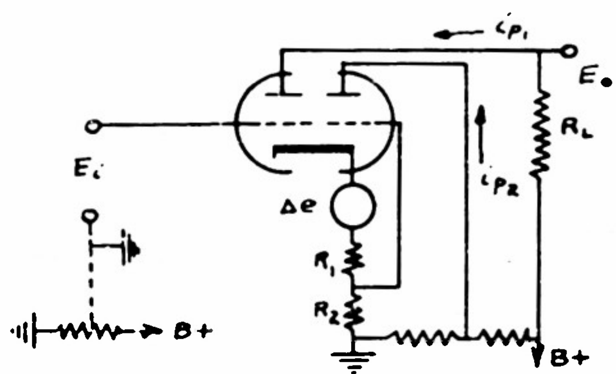


Figure 3.2 - Miller Circuit

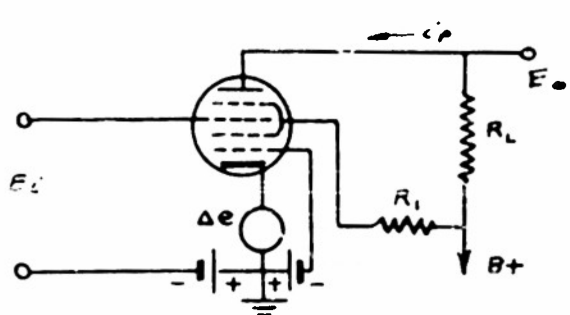


Figure 3.3 - Emission Compensator Using a Pentagrid Tube

variation, but can be made so, as can the diode compensator, by applying a portion of the plate voltage into the input circuit, as shown in the dotted connection in Fig. 3.2, by means of a properly tapped voltage divider in the plate supply.

Compensation both for effects of heater voltage change and those due to random changes of emission can be obtained in a pentagrid type tube by use of a circuit as shown in Fig. 3.3 (19). In this circuit R_1 is adjusted to make grids one and four have equal and opposite transconductance to the plate. Therefore any change of emission caused by heater voltage variation or cathode emission variation will cancel out in the plate circuit. Plate voltage compensation may be applied by a tapped divider as in the Miller and diode compensator circuits.

Another compensation scheme that may be applied to a pentagrid tube is shown in Fig. 3.4. Here as before grid number three serves as the control grid. The screen grid is supplied from a low impedance source and furnishes a large portion of the cathode current. Cathode resistor R is made large so that drift voltage, Δe, causes little change in cathode current, hence practically all of the drift voltage is developed with reversed polarity between cathode and ground. The voltage developed in the cathode circuit changes the bias on grids numbers one and two in a direction to largely neutralize the effects of drift. Degeneration due to the large

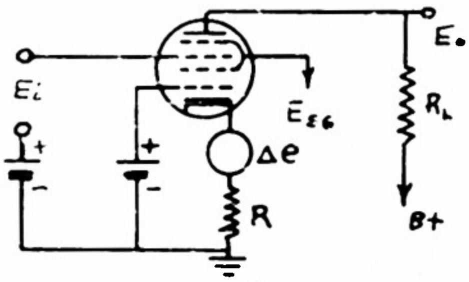


Figure 3.4 - Emission Compensator Using a Pentagrid Tube.

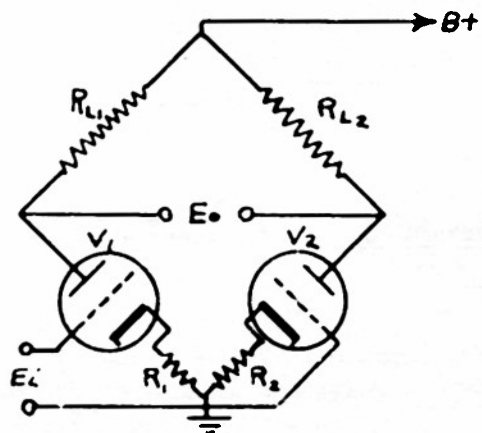


Figure 3.5 - Parallel Bridge Circuit

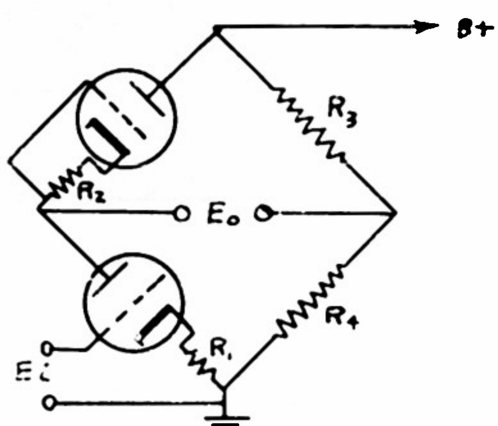


Figure 3.6 - Series Bridge Circuit

cathode resistor is small because plate current is made small compared to screen current by employing a high resistance plate load resistor. Caldecourt (12) describes an electrometer amplifier in which a type 12BE6 pentagrid tube is used as the electrometer tube. A circuit similar to Fig. 3.4 is employed. An improvement in zero point drift of about seven times over that of an uncompensated circuit is obtained. Plate voltage compensation is obtained by applying a portion of the plate voltage supply to grid number one.

A bridge balanced circuit remains balanced over a wider range of power supply voltages than the simple compensation circuits if identical tubes are used in the individual arms. A conventional bridge amplifier is shown in Fig. 3.5. Practically the same requirements of tube balance and adjustment as specified for the electrometer bridge circuit are necessary here. Double triodes are useful in this circuit since there is the greater probability of obtaining a close match between sections of such a tube than with individual tubes.

An alternate bridge circuit, which has several advantages over the parallel circuit is shown in Fig. 3.6 (20). Here the balance is no longer for tubes in parallel, but rather in series, and both tubes pass the same plate current at zero-signal position. A difference of cathode emission between the two tubes will shift the zero position less with the same plate current in each tube. The circuit can be carried a step further and resistors R_3 and R_4 replaced by

a similar series arrangement of tubes. The output circuit is then push-pull and is useful for deflecting the beam in a cathode-ray tube.

One way to avoid the drift difficulties of a d-c amplifier is to allow the d-c signal to modulate an a-c carrier. After sufficient amplification in an a-c amplifier the modulated carrier is detected to recover the amplified d-c signal. In photo-tube work and in the measurement of various forms of radiation using high speed bolometers and thermocouples, it is possible to interrupt the radiation by means of a mechanical shutter and thus directly obtain an a-c output that is proportional to the incident radiation. Another type of modulator that is used with relatively low impedance circuits is the "chopper", which consists of vibrating contacts that interrupt the d-c signal at a fixed rate and hence generate a carrier signal that is proportional to the d-c signal.

High impedance circuits usually employ a dynamic condenser modulator. In this type of modulator, one plate of a condenser is electrically driven so as to vibrate at a fixed amplitude relative to the other plate. The d-c signal introduces a charge on the plates, which by their relative motion change the capacity, and hence generate an a-c voltage between the plates that is proportional to the d-c signal. A modulator of this type is used in the vibrating reed electrometer and the vibration multiplier which is used in computers.

The nonlinear characteristics of a vacuum tube may also be used as modulators for this type of work. Lampitt (21) has developed a modulated carrier d-c amplifier using a balanced bridge input circuit with a pair of matched tubes as modulators. A block diagram is shown in Fig. 3.7. An oscillator generates the carrier, which is introduced by blocking capacitors to the grids of the modulator tubes. With zero d-c signal at the input, no carrier is transmitted to the input of the a-c amplifier. A signal introduced on the input will cause the plate resistance of one of the tubes in the bridge circuit to change, hence up-setting the balance and generating an a-c signal at the input to the a-c amplifier. For maximum sensitivity the modulator tubes are operated in the nonlinear portion of their plate characteristics so as to produce a large change in plate resistance for a given input signal. Vacuum tubes as modulators in this type of d-c amplifier are of little value as far as drift is concerned, since any change in tube characteristics will be equivalent to a signal input as in a conventional d-c amplifier. The most stable modulators are usually circuit elements such as resistance, inductance, and capacitance, which can be made more stable than vacuum tubes.

Modulated carrier systems are limited in band-pass characteristics by the carrier frequency, which must be high if wide band width is to be obtained. Many of the mechanically

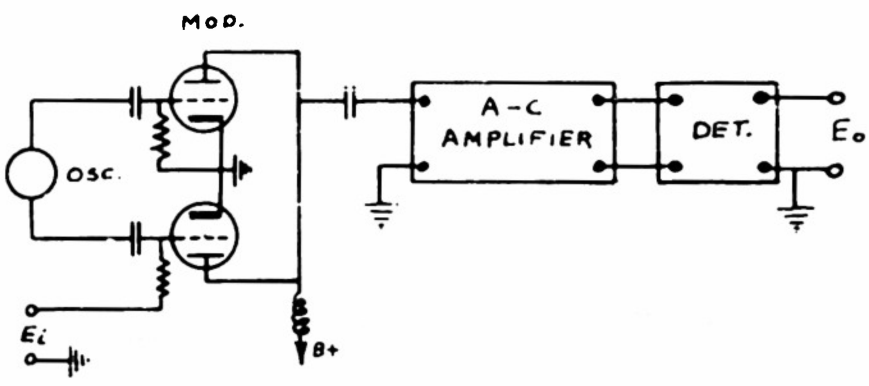


Figure 3.7 - A D-c Amplifier Using a Modulated Carrier System

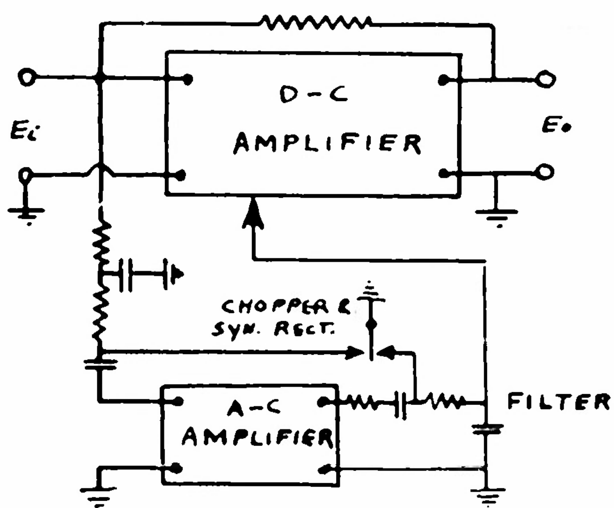


Figure 3.8 - A D-c Amplifier With Drift Corrector

driven modulators are thus limited as to band-pass characteristics. Goldberg (22) has devised an ingenious d-c amplifier which overcomes these limitations. A block diagram is shown in Fig. 3.8. A conventional feedback amplifier is employed, but a chopper modulator is used to convert the drift voltage into an a-c signal which is amplified, detected (by extra contacts on the chopper), and used to correct the d-c amplifier for drift. This system utilizes the fact that the input to a unity feedback amplifier is the only point where the signal can be separated from drift. The signal relative to ground at the input is reduced by feedback to a factor equal to the open loop gain, while the full drift voltage is present at this point due to the feedback loop. The d-c amplifier can be designed in the usual manner for a wide band-pass while the a-c amplifier need have only a narrow band-pass in order to pass the slowly varying drift signal.

SECTION 4

ELECTRONICALLY STABILIZED POWER SUPPLIES

This section will present some of the problems encountered in the design of electronically stabilized power supplies used in conjunction with electrometer tube circuits. Attention will be directed to the simple degenerative stabilizer (23), since it is the most widely used and generally satisfactory for this type of work. A description of two experimental supplies, together with performance data, will be given.

4.1 The degenerative stabilizer.--In its most simple form, the degenerative stabilizer consists of a triode tube in series with the unstabilized power source, which consists usually of the standard transformer-rectifier-filter combination, and the load as shown in Fig. 4.1(a).

One figure of merit of a stabilized power supply is the stabilization ratio, S_o. It is the ratio of the proportionate change of input voltage to a proportionate change of output voltage. That is,

$$S_o = \frac{\frac{\Delta E_i}{E_i}}{\frac{\Delta E_o}{E_o}} = \frac{\Delta E_i}{\Delta E_o} \frac{E_o}{E_i} . \quad (1)$$

Assuming for the moment that the supply has a constant load and that the stabilization is sufficient to hold the change of load current (with variation of E_i) to a negligible amount, then the equivalent circuit of Fig. 4.1(b) may be simplified to that of Fig. 4.1(c). From which there follows that

$$\Delta E_i - \mu e_g = \Delta E_o , \tag{2}$$

and

$$e_g = \beta \Delta E_o , \tag{3}$$

where $\beta = \frac{R_1}{R_1 + R_2}$ (e_g develops across R_1)

From which the stabilization factor becomes

$$S_o = (\mu\beta + 1)\frac{E_o}{E_i} . \tag{4}$$

For a large stabilization ratio it is necessary for the control tube to have a large amplification factor, μ. The stabilization factor can be increased by adding amplification so that the effective gain of the control tube is increased. This is illustrated in Fig. 4.1(d), which gives

$$e_g = K[\beta \Delta E_o] , \tag{5}$$

Where $\beta = \frac{R_2}{R_1 + R_2}$ (input voltage to amplifier developed across R_2)

K = Voltage gain of amplifier.

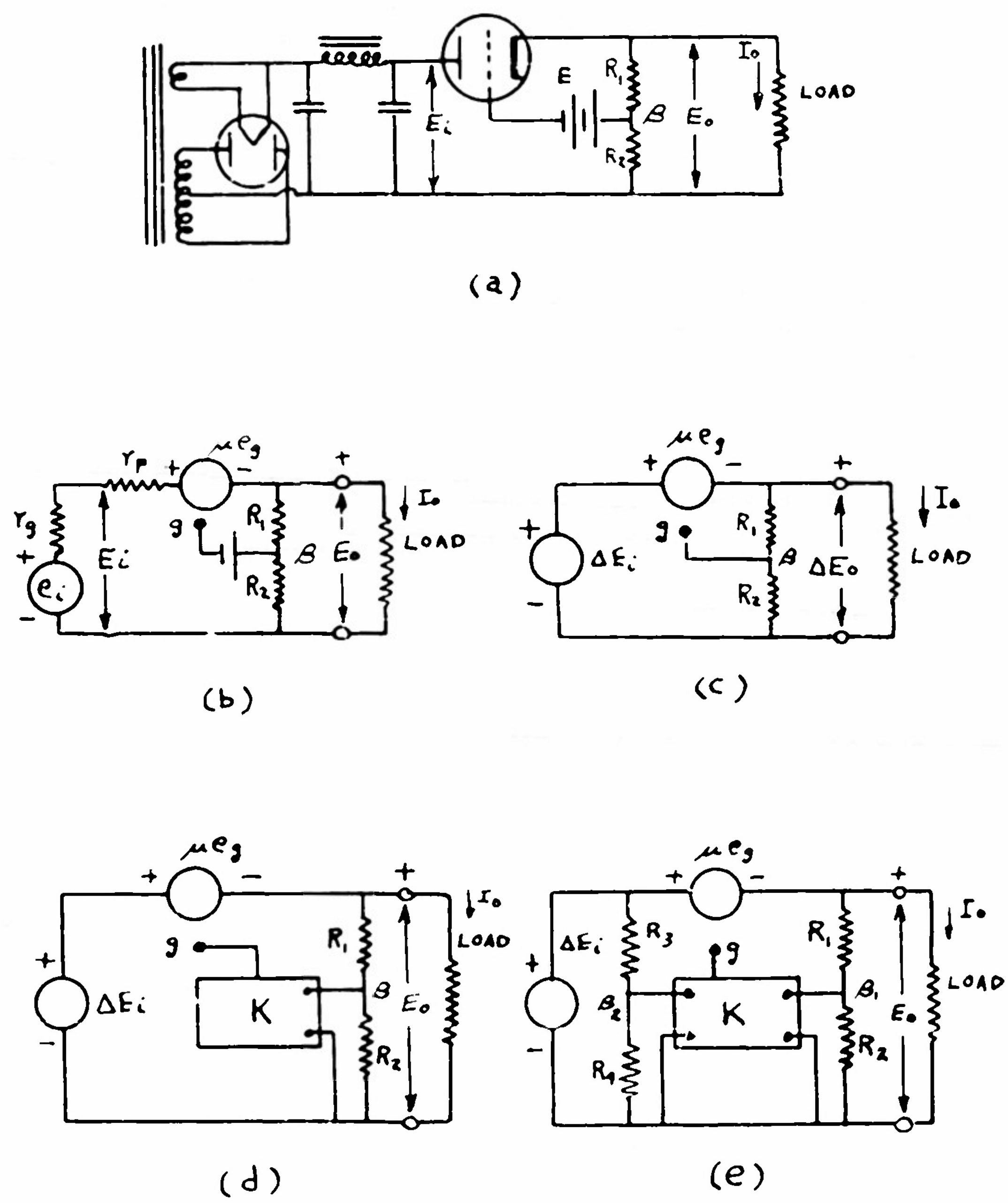


Figure 4.1 - The Degenerative Stabilizer

Using equations 5, 2, and 1 and solving for S_o gives

$$S_o = (\mu K_1\beta + 1)\frac{E_o}{E_i} . \qquad (6)$$

From equation 6 it appears that infinite gain is necessary in the amplifier in order to have perfect regulation ($S_o = \infty$). A simple scheme known as compensation provides a means of obtaining large stabilization ratios. Compensation consists of applying a small amount of the unstabilized voltage, E_1, to the amplifier. This is illustrated in Fig. 4.1(e). The voltage at the gri. control tube now becomes

$$e_g = K(\beta_1 \Delta E_o + \beta_2 \Delta E_i). \qquad (7)$$

Where, $\beta_1 = \frac{R_2}{R_2 + R_1}$

$\beta_2 = \frac{R_4}{R_4 + R_3}$

The stabilization factor now becomes

$$S_o = \left(\frac{1 + \mu K\beta_1}{1 - \mu K\beta_2}\right)\frac{E_o}{E_i} . \qquad (8)$$

For perfect stabilization,

$$\beta_2 = \frac{1}{\mu K} . \qquad (9)$$

The voltage output of the stabilized power supply, assuming K is large, is given by

$$E_o \approx E \frac{R_2 + R_1}{R_1} \tag{10}$$

Where, E = Voltage of battery in grid circuit of control tube or amplifier.

The purpose of the battery with voltage, E, is to cancel out a large portion of the voltage, βE_o, so that only changes in the output voltage, $\beta \Delta E_o$, appear at the input to the amplifier. The voltage, E, is called the reference voltage, because a portion of the output voltage, βE_o, is compared with it in order to obtain $\beta \Delta E_o$. The voltage $\beta \Delta E_o$ is called the error signal, and the amplifier, of gain K, the error amplifier.

Equation 10 shows that the long-time stability of the stabilized power supply depends to a large extent on the stability of the reference voltage, E, and the sampling resistors R_1 and R_2.

<u>4.11 The error amplifier.</u>--The error amplifier must amplify signals that extend down to zero frequency and thus encounters problems associated with d-c amplifiers. Drift in the error amplifier is equivalent to a change of reference voltage E. Many of the d-c amplifier circuits used to minimize drift are necessary in the low level stages of the error amplifier for best stability.

<u>4.12 Reference elements.</u>--The problem of a stable reference element is one of the most important with stabilized power supplies. This problem is usually more serious than drift in properly designed error amplifiers.

The nonlinear volt-ampere characteristics of a glow discharge tube offers a simple and convenient means of obtaining a reference voltage. Small neon lamps have often been used but have quite variable characteristics. Glow-tubes especially designed for use as voltage stabilizers, such as the OB2, OB3, OC3, etc. are much more uniform of characteristics due to greater care in construction and testing. Vibration and change of position do not adversely affect stability. The most serious objection to glow-tubes is mode shifting, that is a spatial redistribution of the glow discharge over the electrodes, when the tube is ignited, when current is changed, or for unapparent reasons. Mode changes are evident as sudden changes in the voltage across the tube and may amount to from 0.1 to 0.5 volt. For maximum stability, a glow tube should be operated at currents at which mode changes are at a minimum. This is usually a compromise, since large currents reduce tube life and currents that are too small result in erratic operation. Drift rate varies with current and tube age and is usually positive for the first few hours and then becomes negative which continues throughout tube life at about 200 μV per minute (24). Temperature variations are less than 1/2 per cent over a temperature range from 25 to 80 degrees centigrade.

Dry cells offer an excellent means for obtaining a constant reference voltage if currents are limited to very small values. An accuracy of 0.05 per cent over several

months can be obtained from dry cells when operated under the following conditions:

1. Fresh batteries.
2. Very low currents (less than one $\mu a.$)
3. Constant temperature (within a few degrees with a maximum not over 25 degrees centigrade)

An electronically regulated power supply using Burgess Z30N batteries as reference, when checked over a period of 20 days, was constant to about 0.05 per cent (24). The temperature coefficient of dry cells is about 0.02 per cent per degree

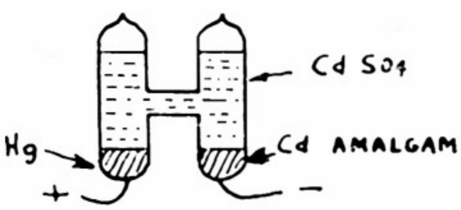


Figure 4.2 - Standard Cell

over a temperature range of -55 to 70 degrees centigrade.

In applications where a very precise reference is required, standard cells are used. The most widely used standard cell is the Weston unsaturated cadmium type. This cell is contained in an H-shaped glass vessel, with platinum wires sealed through the bottoms for connection with the electrodes. A sketch of such a cell is shown in Fig. 4.2. The positive electrode consists of pure mercury and the negative electrode consists of a cadmium amalgam. The cell is filled with a solution of cadmium sulphate saturated at

four degrees centigrade. The voltage of unsaturated standard cells varies slightly between cells, but the individual cell is constant to within ± 0.01 per cent over a temperature range of -16 to 15 degrees centigrade.

A super regulated power supply, used as a standard for calibrating instruments and general laboratory use, is manufactured by Radiation, Inc. of Melbourne, Florida. This instrument supplies voltages in steps of 0.01 volts from zero to 109.99 volts within 0.05 per cent into a load as low as 1000 ohms, and current in steps of 0.01 ma. from zero to 109.99 ma. within 0.05 per cent into a load as low as 1000 ohms. The internal reference is a standard cell similar to the Weston.

4.2 Experimental power supplies. --Two electronically stabilized power supplies were especially constructed for powering electrometer tube circuits. The first is used for powering a unity feedback current amplifier, in conjunction with a Victoreen type VX-41A electrometer tube. The second is used for powering an FP-54 electrometer tube in a Barth type circuit. A more complete description of the electrometer circuits will be given in section 5.

A circuit diagram of the power supply for the feedback amplifier is shown in Fig. 4.3. This supply consists of two sections, one for the heater circuit and the other for the plate circuit. The heaters of all tubes excepting those of the control tubes and rectifiers are heated from the stabilized output of the upper supply as shown in Fig. 4.3. A type 6AS7 control tube is used, and has the advantage that the current

requirements, of approximately 150 ma., can be met with a single tube. It also has the disadvantages of a low amplification factor, which reduces gain, and also requires a large grid voltage swing for adequate control. The error amplifier consists of one type 12SL7 and one type 12AT7 tubes, in modified Miller circuits in which R_2 is zero. This modification allows both grids to be used as in a difference amplifier while at the same time providing appreciable cathode compensation. A Burgess type 10308 45 volt dry cell battery serves as the reference voltage source. Precision wire wound resistors are used in all parts of the circuit where slight changes in resistance would lower stability. Compensation is introduced by feeding a small portion of the unstabilized voltage to the grid of the last stage of the error amplifier. The 10K potentiometer provides an adjustment for compensation. Since the voltages in the heater supply section are relatively low, the plate supply for the error amplifier is obtained from the plate supply section.

The current requirements of the plate supply section are moderate and can be easily controlled with a type 6Y6-G tube, triode connected. A 6Y6-G tube, triode connected, has an amplification factor of approximately six while the 6AS7 tube has an amplification factor of only two. The error amplifier is essentially the same as for the heater supply except that an additional 45 volt dry cell battery provides a total

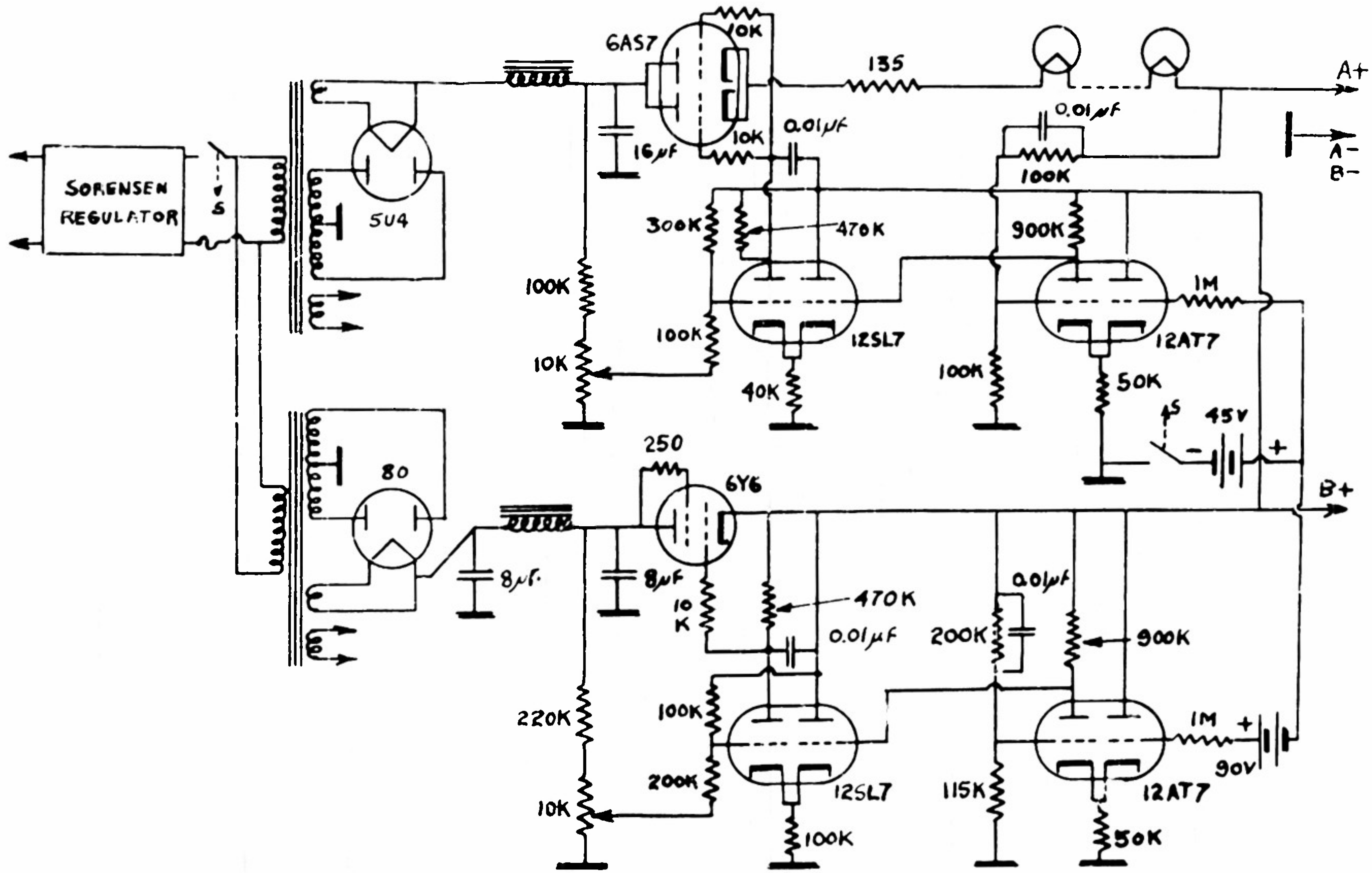


Figure 4.3 - Diagram of Stabilized Power Supply For Feedback Electrometer Circuit

reference voltage of 90 volts. The higher reference voltage being desirable since the loss of gain in the sampling circuit is then smaller. Compensation is applied in the same manner as in the heater supply section. Compensation was adjusted by canceling most of the output voltage of the supplies with batteries and measuring changes of output voltage with a one volt full scale meter. A variac was used to vary the line voltage over a range from about 105 to 130 volts. The 10K potentiometers were then adjusted to minimize the effect of slow changes in line voltage. By proper adjustment compensation can be used to reduce output variations to within one mv. for a ten per cent change in line voltage. Output voltage variation of the plate supply over several hours of operation are shown in Fig. 4.6. The different plots are for runs on different days, with the small differences probably being due to ambient temperature effects on the reference batteries. The reference batteries are located outside of the power supply cabinets in order to isolate them from the heat from the power supply. A Sorensen regulator is used in the power line feeding the power supply in order to reduce line fluctuations to a magnitude that the error amplifiers can handle without overload.

The plate supply section of this power supply furnishes approximately 258 volts at 40 ma. with a ripple of 0.3 mv. The heater supply section furnishes approximately 109 volts at 150 ma. with a 3 mv. ripple.

A circuit diagram of the second power supply is shown in Fig. 4.4. It provides an output voltage of approximately 194 volts at 100 ma. Two parallel 6Y6-G tubes, triode connected, are used as control tubes. The error amplifier consists of two type 12AX7 double triode tubes. The heater power for the error amplifier tubes is stabilized with an Amperite ballast tube. The reference voltage is obtained from a type OB3 glow discharge tube operated at a current of near nine ma. from the stabilized output in order to reduce mode changing effects. The unstabilized supply variations were reduced somewhat by using choke input but, the allowable current variations in the load are limited (0-120 ma) owing to the inability of the error amplifiers to fully drive the control tube. These limitations occur mainly because the error amplifier plate supply is obtained from the relatively low output voltage. Control is lost below 105 volts line voltage due to an inadequate voltage from the unstabilized supply source. This could be corrected by using a power transformer with higher secondary voltage. Compensation is adjusted by the 300 ohm potentiometer in the sampling circuit. Fig. 4.5 shows the improvement obtained by compensation. A high wattage, low temperature coefficient, series resistor is used to drop the voltage to the requirement of the electrometer circuit. From Fig. 4.7, it can be seen that the voltage is slightly different each time the supply is turned on. By adjusting the 50 ohm variable resistor for minimum

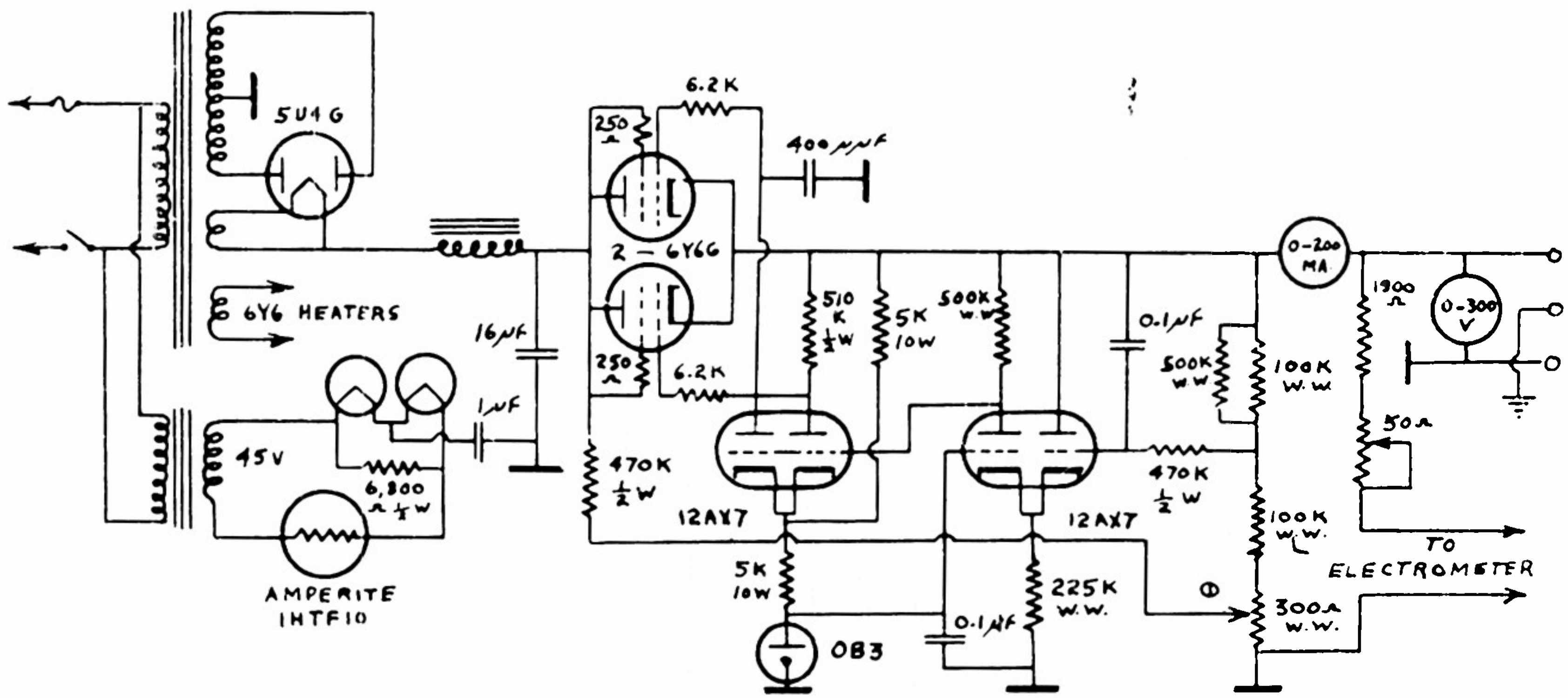


FIG. 4.4 --SCHEMATIC OF POWER SUPPLY FOR FP-54
ELECTROMETER TUBE CIRCUIT

galvanometer deflection, these effects can be compensated, while also assuring that the electrometer circuit is balanced. When properly adjusted a line voltage change from 110 to 125 volts makes no noticeable deflection on the galvanometer in the electrometer circuit.

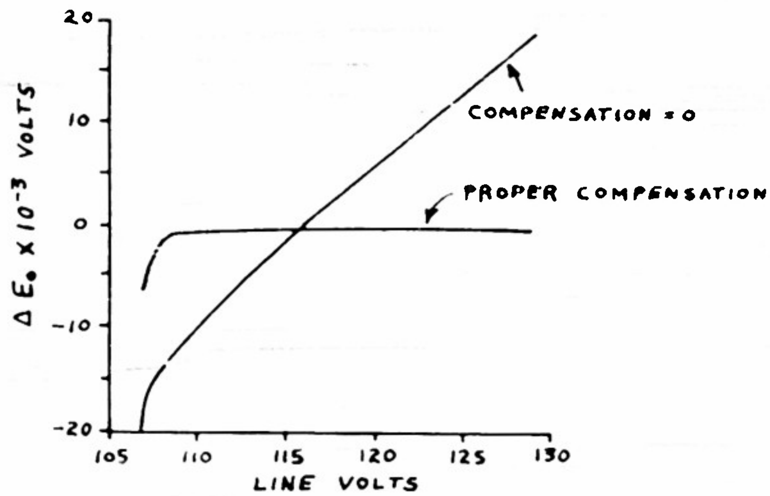


Figure 4.5 - Effect of Compensation on Power Supply

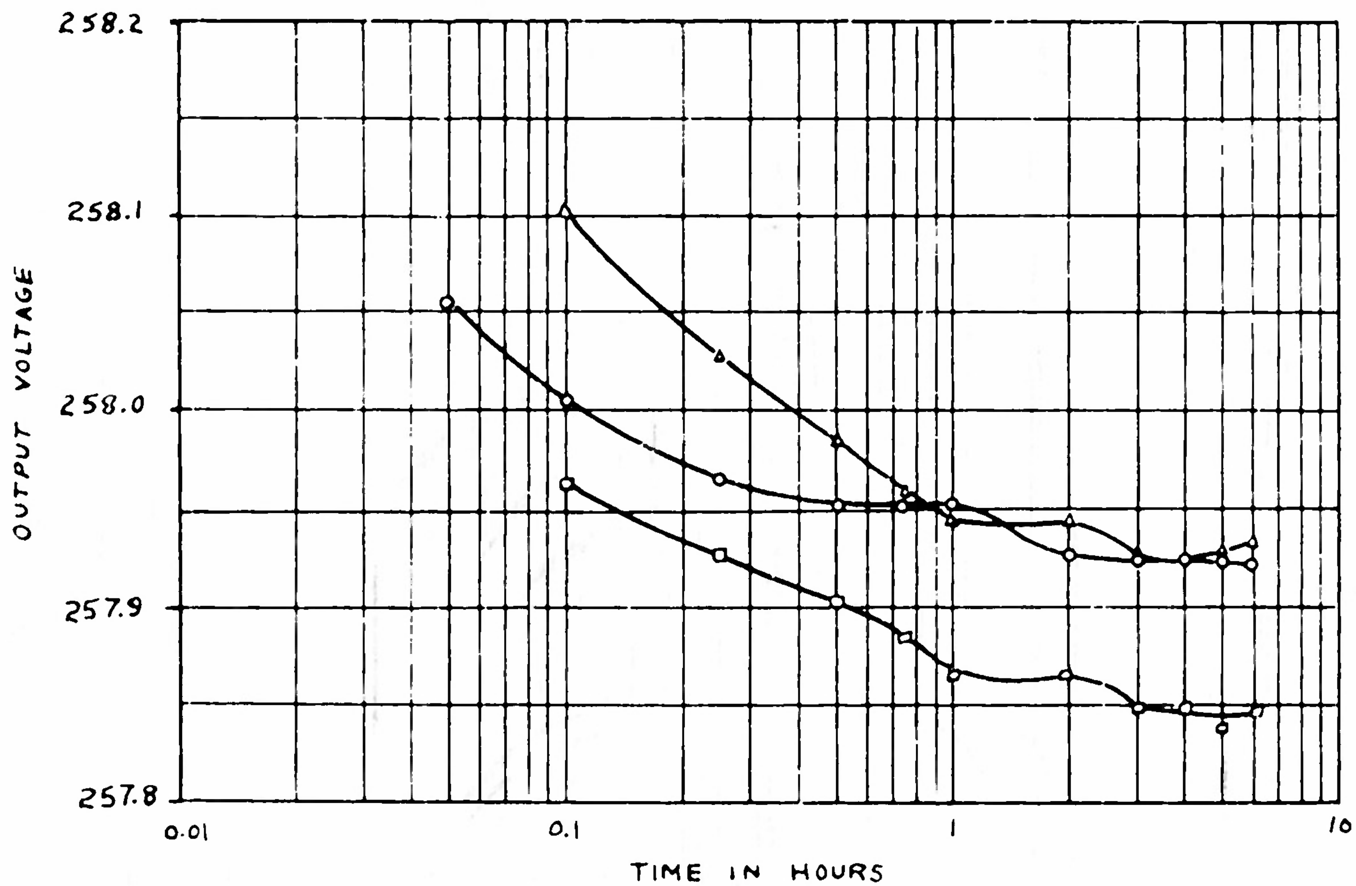


FIG. 4.6-- OUTPUT VOLTAGE CHARACTERISTICS OF POWER SUPPLY WITH DRY CELL BATTERY AS REFERENCE ELEMENT.

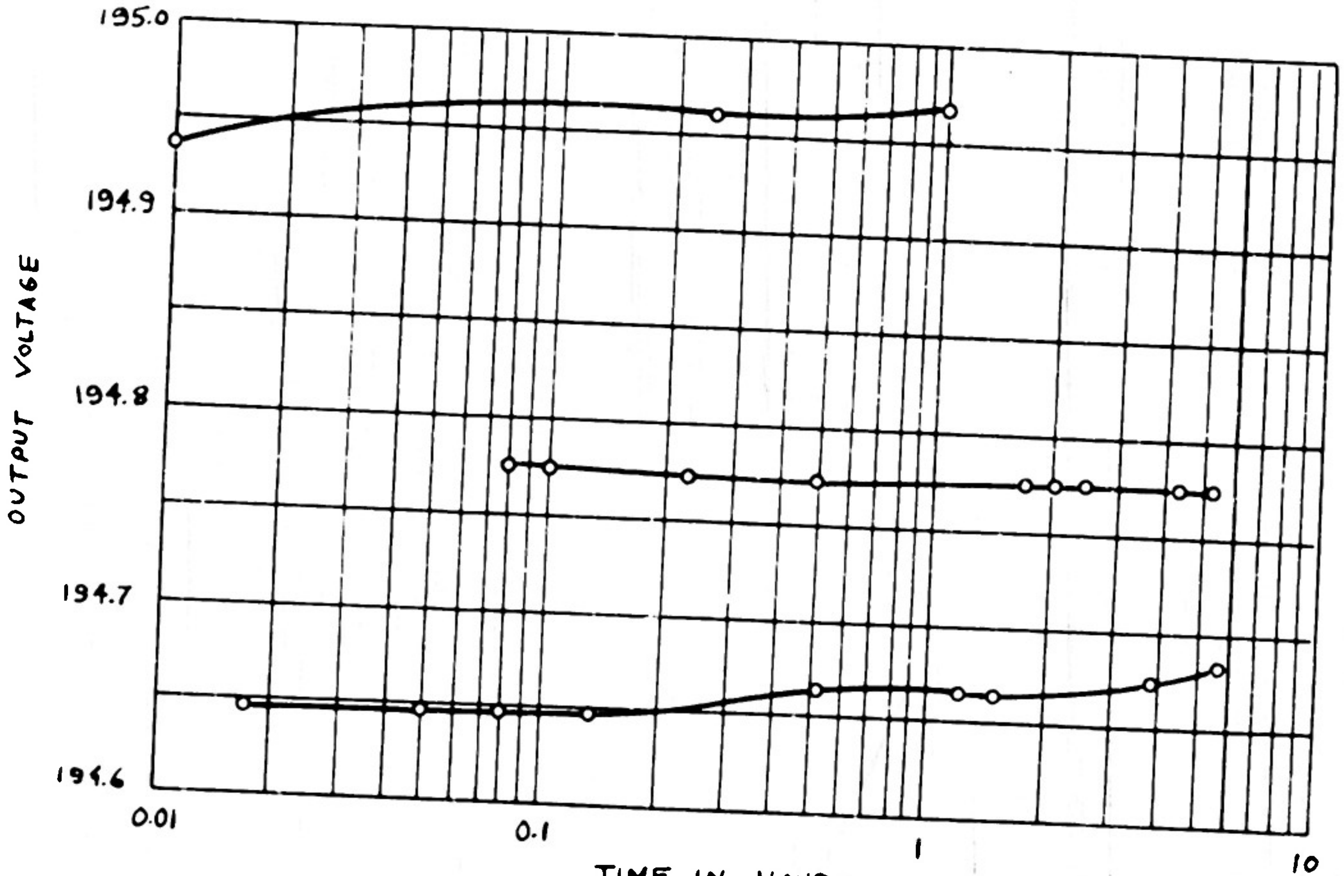


FIG. 4.7--OUTPUT VOLTAGE CHARACTERISTICS OF POWER SUPPLY WITH GLOW-TUBE AS REFERENCE ELEMENT.

SECTION 5

DESCRIPTION OF THREE EXPERIMENTAL ELECTROMETER CIRCUITS

This section will present a description of three electrometer circuits. The first is an a-c line powered, unity feedback current amplifier used in conjunction with a VX-41A electrometer tube. This amplifier measures the ion currents in a mass ..eter especially designed for the study of negative gaseous ions. The second electrometer circuit is a completely a-c line powered circuit with a type FP-54 electrometer tube and a galvanometer indicating device. The third electrometer is entirely in the experimental stage, and is an attempt to use the properties of nonlinear capacitors (25, 26) as modulators in a modulated carrier type of electrometer d-c amplifier.

<u>5.1 Unity feedback electrometer amplifier.</u>--This amplifier contains two complete measuring circuits powered from the same stabilized power supply. A circuit diagram of one of these amplifiers is shown in Fig. 5.1. This circuit is similar to a circuit used by Nier (14). The electrometer tube is housed in a small brass box which can be placed near the ion collectors of the mass spectrometer, and is connected to the main amplifier via shielded cables. The electrometer circuit is of the modified

DuBridge and Brown type (8). Since the output of such a circuit is balanced and above ground potential a Miller (17) type of compensated input type of circuit is used on the input to the amplifier. As in the power supply error amplifiers, these are modified Miller circuits in which R_2 is made zero so that both grids may be used as a difference amplifier. The remaining portion of the amplifier is a conventional d-c amplifier with a cathode output stage. Batteries are used to bring the steady state component of the output of the cathode followers to ground potential. Drift in battery voltage at this point in the circuit is not too serious since drift is reduced by a factor equal to the open loop gain of the amplifier. Maximum current drain on the batteries is rarely over 100 μa., since the indicating meter has a sensitivity of 100 μa. full scale. If a negative source of stabilized voltage of about -100 volts were available the grounded side of the cathode resistor of the cathode follower could be connected to this potential source thus bringing the cathode potential near to ground potential and eliminating the need for the batteries. The indicating meter in conjunction with the range switch and series resistors forms a voltmeter with full scale sensitivity of 5 mv., 50 mv., 100 mv., and 1 volt. As shown in Appendix I, a unity feedback d-c amplifier has a steady-state voltage gain very near one, hence the indicating meter reads the voltage across the input resistor at the grid of the electrometer tube

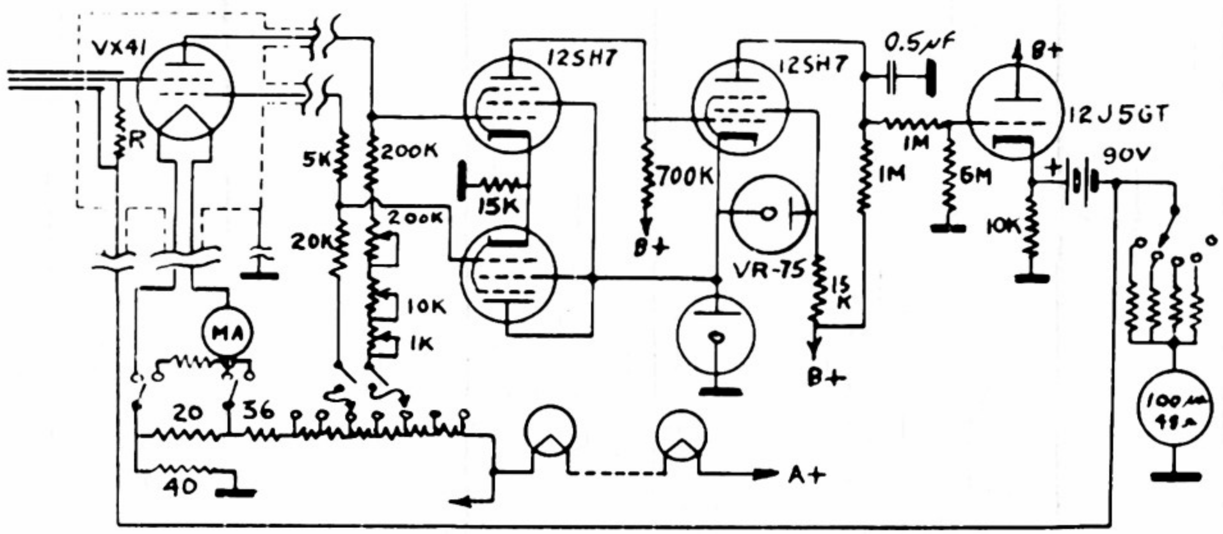


FIG.5.1 -- FEEDBACK ELECTROMETER TUBE AMPLIFIER

to a high degree of accuracy. In this circuit a grid resistor of approximately 10^{11} ohms is used in each electrometer grid circuit and with the voltage ranges stated above this gives full scale current sensitivities of 5×10^{-14}, 5×10^{-13}, 10^{-12}, and 10^{-11} amp.

As with any amplifier with more than two stages and large amounts of feedback, precautions must be taken to reduce the open loop gain to less than one as the phase shift approaches 180 degrees. This amplifier contains at least six energy storage elements due to stray capacitances in the individual stages and so would oscillate if the 0.5 μf condenser were not placed across the plate load resistor of the last pentode stage. Thus, the half-power frequency of this stage is made so low compared to the other stages that for all practical purposes the open loop amplifier can be considered to have a single energy storage system. When the feedback loop is closed an additional large time constant circuit is added due to the high value grid resistor and the input capacity of the electrometer tube. As shown in Appendix II the system output can contain damped oscillations after the application of a step signal unless circuit constants are adjusted to reduce these effects. The shields surrounding the grid leads of the electrometer tube are connected to the feedback lead in order to alter the feedback at higher frequencies and thus increase transient stability. It should be noted, however, that such a practice also increases the

time constant of the input circuit and hence is a compromise between speed of response and transient stability.

A switch is provided so that plate and space charge grid voltages may be turned on after the filament in the electrometer tube has reached operating temperature and allows removal of these voltages before the filament is turned off. Failure to preheat the cathode causes an increase in long-time drift. This is believed to be caused by momentary operation of the filament under temperature limited conditions that tend to destroy the very thin emitting surface which is then slowly replenished, resulting in emission drift.

Drift of amplifier number two is less than number one. Tests over a period of six hours showed that drift in amplifier number two was not over a half of a mv. after approximately a four hour warm up.

The advantages of a feedback amplifier for this type of work are:

1. Sensitivity independent of tube and circuit parameters.
2. Apparent capacity of input circuit reduced.
3. Greatly improved linearity.
4. Low output impedance.

<u>5.2 Single tube electrometer circuit.</u>--A circuit diagram of this electrometer is shown in Fig. 5.2 It is essentially the same as the modified DuBridge and Brown circuit described

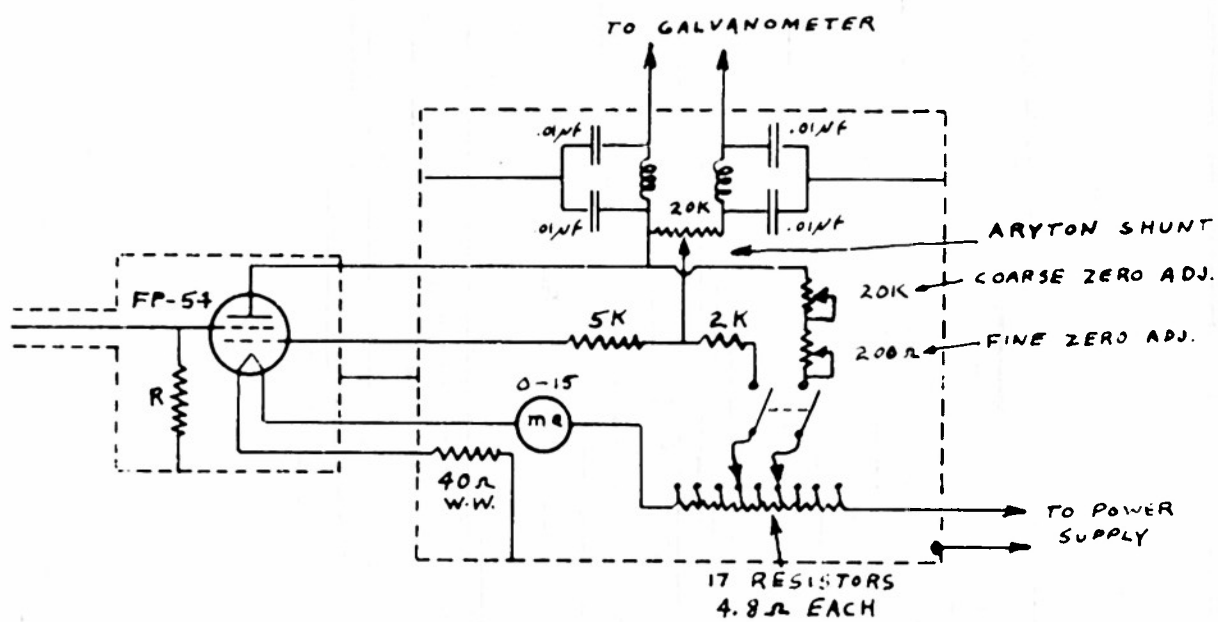


FIG. 5.2 -- FP-54 ELECTROMETER TUBE CIRCUIT

in Section 2. This electrometer circuit is entirely powered from the a-c line by the stabilized supply described in Section 3. The complete electrometer consists of four parts, the power supply, control unit, electrometer tube with shield, and galvanometer, which are interconnected by shielded cables so wired that accidental connection of the wrong units can do no damage. The unit containing the electrometer tube is made of approximately 1/4 inch thick soft iron to provide some degree of magnetic shielding for the tube when used near magnetic fields such as are encountered near the electromagnets of a mass spectrometer. The 2K and 5K resistors in the space charge grid circuit are precision wire-wound units. The other resistors in the circuit, including the special tapped resistor, were wound with manganin wire on Lucite forms. The Aryton shunt and coarse zero adjustment controls are General Radio type 471-A potentiometers. The fine zero adjustment is a General Radio type 214-A potentiometer. The use of good quality parts is an absolute necessity in this type of circuit. A Leeds & Northrup, Type E, galvanometer with a sensitivity of 3.6×10^{-10} amp/mm. gives a maximum voltage sensitivity of 24,000 mm/volt. A grid resistor of 10^{11} ohms allows a maximum current sensitivity of 4.1×10^{-16} amp./mm.

<u>5.3 Nonlinear capacitor electrometer.</u>--The nonlinear characteristics of certain ceramic materials, as a function of applied

voltage offer the possibility of constructing a stable modulator for a modulated carrier d-c amplifier. Fogle (27) has conducted tests on samples of ceramics from various manufacturers. He found that the American Lava Company type T-128 ceramic material had the largest rate of change of capacity with voltage. The characteristics of this sample are shown in Fig. 5.3. Resistivity data is not generally

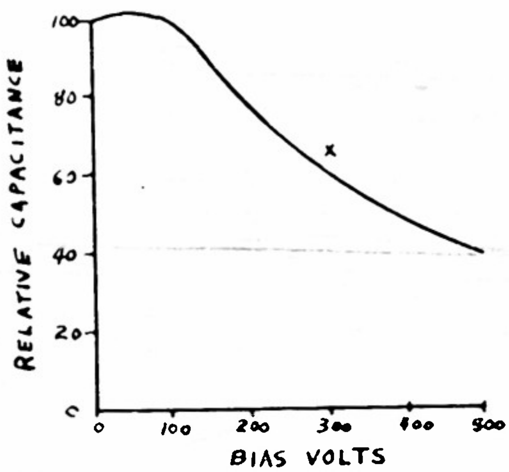


Figure 5.3 - Characteristics of Nonlinear Capacitor

available, but the General Ceramic type 8-7 is specified to have a resistivity of 6×10^{14} ohm-cm.

Fogle has designed an amplifier using this type of capacitor. The variations of the capacity of the ceramic condenser with applied signal causes frequency modulation of an r-f oscillator, which in turn feeds into a slope type discriminator that recovers the amplified signal.

Several tests were made of a bridge type modulator using nonlinear capacitors. The circuit is shown in Fig. 5.4.

Nonlinear capacitors are used in two legs of the bridge circuit in order to cancel temperature effects, since nonlinear capacitors have a rather large temperature coefficient. An r-f oscillator with a frequency of approximately 175 kc. supplies the excitation voltage at point a-a. The secondary of the transformer resonates with the capacity of the bridge at points a-a at this frequency. By action of blocking

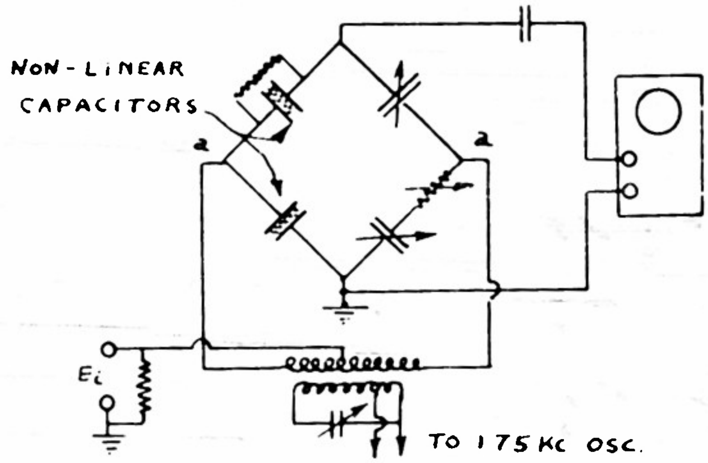


Figure 5.4 - Nonlinear Capacitor Modulator

condensers, the input signal is applied to the lower nonlinear capacitor only. The output of the bridge circuit is indicated on an oscilloscope. With this rather crude setup, about five volts was necessary on the input circuit in order to detect any unbalance in the bridge circuit. Larger and more linear capacity changes are possible if the ceramic condenser is biased to point X on the characteristic curve as shown in Fig. 5.3, but this imposes the additional problem of obtaining a stable bias source.

Perhaps a doubly resonant bridge circuit as used by Cook (28) to detect minute changes in capacity would prove useful here. In Cook's circuit the input from the oscillator is resonated with the capacity of the bridge circuit in order to provide large circulating currents. The output of the bridge circuit is also resonated with the input transformer to the carrier amplifier. Capacity changes as small as 0.001 $\mu\mu f$ can be measured with this type of circuit.

SECTION 6

SUMMARY AND CONCLUSIONS

Methods for the measurement of small direct currents, using vacuum tube amplifiers, have the following advantages over the now almost obsolete methods using quadrant electrometers:

1. Relative ease of installation and adjustment.
2. Considerable ruggedness and dependability.
3. High degree of linearity and stability of sensitivity when negative feedback is used.
4. Increased speed of response.

The greatest single difficulty with electronic methods for the measurement of small direct currents is drift of the zero of the indicating device. After drift due to changes in circuit parameters and supply voltages have been minimized, the remaining drift is due to variations in vacuum tube parameters. Some of the various types of circuits and tubes devised for neutralizing these effects have been discussed. The split electrometer tube and modulated carrier systems offer the greatest immunity to drift.

The smallest current that can be measured with an electrometer tube, such as described in this thesis, is limited due

to fluctuations caused by thermal effects in the grid resistor and the shot effect in the tube. Hafstad (29) has shown that the maximum sensitivity from an FP-54 tube can be obtained with a "floating grid" provided the tube is held in a chamber under reduced pressure. The grid thus automatically assumes a potential (near -2.5 volts) such that grid currents are at a minimum and grid resistance can be assumed to be approximately 10^{14} ohms. A measure of fluctuations under these conditions shows that a current of 3×10^{-19} amp, or two electrons per second could be detected. As the time constant of the grid circuit is 300 sec., it would take several minutes to detect such a signal. Thus speed of response must be sacrificed for maximum sensitivity. Another way of saying this is that bandwidth is reduced in order to improve signal-to-noise ratio.

An a-c line powered, unity feedback, electrometer amplifier has been constructed for measuring the small ion currents in a mass spectrometer designed for the study of negative gaseous ions. This amplifier has been in use about eight months and has satisfactorily low drift rate, if allowed to warm up for about four hours before use.

A second electrometer circuit that is entirely powered from the a-c line has been constructed and tested but has not as yet been used. A glow-tube is used as the reference in the power supply. The effects of small voltage changes that may occur when the power supply is turned on, due to mode

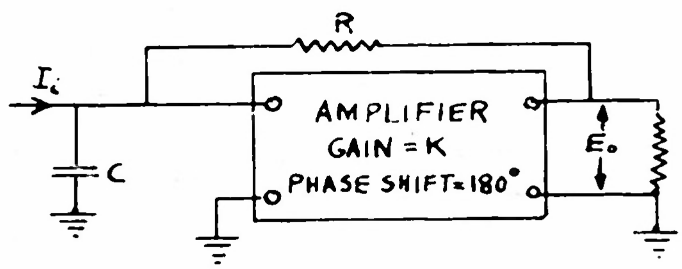
changes in the glow tube, are not serious since the circuit should be balanced before use in any event. This electrometer has a satisfactorily small drift rate although not as low as the feedback electrometer circuit.

A brief study of the possibility of employing the properties of nonlinear capacitors as electrometers tends to indicate that a workable electrometer could be made. Apparently the main limitations would be drift due to the effects of hysteresis and temperature changes. Sensitivity could possibly be improved by using very thin sections of dielectric material to allow a greater potential gradient from the signal. A doubly-resonant bridge circuit would be helpful to obtain maximum sensitivity.

It has been shown in this thesis that the problem of zero point drift in electrometer tube amplifiers can be satisfactorily solved by careful attention to circuit components and stability of the power supply. An electrometer amplifier has been shown to operate satisfactorily without the use of dry cells or storage batteries. A new type of electrometer circuit employing nonlinear capacitors has been proposed. It is hoped that this research will contribute in some small measure to the solution of the general problem of the measurement of small direct currents.

APPENDIX I

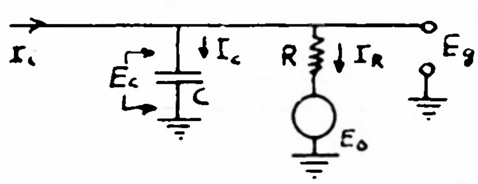
ANALYSIS OF FEEDBACK ELECTROMETER AMPLIFIER WITH CONSTANT 180° PHASE SHIFT AND GAIN



C = input capacitanc :trometer tube and wiring capacitance

R = electrometer grid resistor

I_i = input current



Equivalent Circuit

$$I_i = I_c + I_R \qquad (1)$$

$$E_g = E_c = \frac{1}{C}\int I_c \, d\tau \qquad (2)$$

$$E_g = I_R R - K E_g \qquad (3)$$

Solution of equations 1 and 2 for E_g gives

$$E_g = \frac{1}{C}\int I_i \, d\tau - \frac{1}{C}\int I_R \, d\tau \; . \tag{4}$$

Substitution of equation 3 in equation 4 gives

$$E_g = \frac{\frac{1}{C}\int I_i \, d\tau}{1 + \frac{1+K}{RC}\int d\tau} \; .$$

Since $E_o = K E_g$

$$E_o = \frac{-\frac{K}{C}\int I_i \, d\tau}{1 + \frac{1+K}{RC}\int d\tau} \; . \tag{5}$$

Taking the LaPlace transform and assuming zero initial energy storage, there follows

$$E_o(s) = -\frac{K}{C} \frac{I_i(s)}{S + \frac{1}{RC}(K+1)} \; . \tag{6}$$

Assume a unit step change in I_1 gives $I_i(s) = \frac{I_i}{S}$

$$E_o(s) = -\frac{K I_i}{C} \frac{1}{S(S + \frac{1}{RC}[K+1])} \tag{7}$$

Tables of inverse transforms (30) give

$$E_o(\tau) = -\frac{K}{K+1} I_i R \left(1 - e^{-\frac{K+1}{RC}\tau}\right) \tag{8}$$

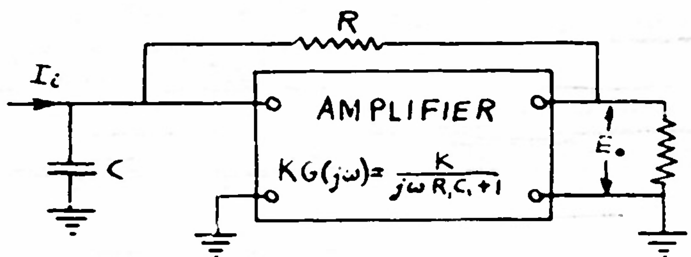
If $K \gg 1$ this simplifies to

$$E_o(t) = -I_i R \left(1 - e^{-\frac{K}{RC}t}\right) \tag{9}$$

This analysis shows that with a unit step of the input current, I_i, that the output voltage rises exponentially to a maximum value $\frac{K}{K+1} R I_i$ with a time constant $\frac{RC}{K+1}$. The important thing to notice is that negative feedback has reduced the time constant of the input circuit, consisting of C and R, by a factor of K + 1 and also that the output voltage is equal to the input voltage by a factor $\frac{K}{K+1}$, which is very near unity for large values of K.

APPENDIX II

ANALYSIS OF FEEDBACK ELECTROMETER AMPLIFIER WITH ATTENUATION AND PHASE SHIFT AT HIGH FREQUENCIES



Attenuation and phase shift at high frequencies are produced by shunting the load resistor of one pentode stage with a 0.5 μf condenser. The transfer characteristics of the amplifier now become

$$KG(j\omega) = \frac{K}{j\omega R_1 C_1 + 1} \qquad (1)$$

Where
$$R_1 = \frac{R_L R_g r_p}{R_L R_g + R_L r_p + R_g r_p}$$

R_L = plate load resistor

R_g = grid resistor of next tube

r_p = plate resistance of tube

C_1 = shunting condenser

When transformed

$$KG(s) = \frac{K}{R_1 C_1}\left(\frac{1}{S + \frac{1}{R_1 C_1}}\right) \qquad (2)$$

If this value of K is substituted in equation 7 of Appendix I, then

$$E_o(s) = \frac{-I_i \frac{K}{R_1C_1} \cdot \frac{1}{S+\frac{1}{R_1C_1}}}{C} \quad \frac{1}{S\left(S+\frac{1}{RC}\left[\frac{K}{R_1C_1} \cdot \frac{1}{S+\frac{1}{R_1C_1}}+1\right]\right)}, \quad (3)$$

which simplifies to

$$E_o(s) = -I_i \frac{K}{CR_1C_1} \left(\frac{1}{S[S+\alpha][S+\gamma]}\right),$$

Where:

$$\alpha = A+B = \left(\frac{RC+R_1C_1}{2RCR_1C_1}\right) + \sqrt{\left(\frac{RC+R_1C_1}{2RCR_1C_1}\right)^2 - \left(\frac{K+1}{RCR_1C_1}\right)}$$

$$\gamma = A-B = \left(\frac{RC+R_1C_1}{2RCR_1C_1}\right) - \sqrt{\left(\frac{RC+R_1C_1}{2RCR_1C_1}\right)^2 - \left(\frac{K+1}{RCR_1C_1}\right)}.$$

Tables of inverse transforms (30) give

$$E_o(\tau) = \frac{-I_i K}{CR_1C_1\alpha\gamma} \left(1 + \frac{\gamma e^{-\alpha\tau} - \alpha e^{-\gamma\tau}}{\alpha-\gamma}\right) \quad (4)$$

or

$$E_o(\tau) = -I_i R\left(\frac{K}{K+1}\right)\left\{1 - e^{-A\tau}\left[\frac{A(e^{B\tau}-e^{-B\tau})}{2B} + \frac{(e^{B\tau}+e^{-B\tau})}{2}\right]\right\}$$

Three conditions of operation can exist, depending on the roots of the characteristic equation in equation 3:

1. $$\frac{K+1}{RCR_1C_1} < \left(\frac{RC + R_1C_1}{2RCR_1C_1}\right)^2 .$$

This is the overdamped condition.

2. $$\frac{K+1}{RCR_1C_1} = \left(\frac{RC + R_1C_1}{2RCR_1C_1}\right)^2$$

This is the critically damped condition.

3. $$\frac{K+1}{RCR_1C_1} > \left(\frac{RC + R_1C_1}{2RCR_1C_1}\right)^2$$

This is the underdamped condition.

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